Multilayer Thermal Insulation Blankets for Terrestrial and Space Applications: Thermal Modelling and Experimental Issues

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Multi-Layer Insulation (MLI) consists of closely spaced shields of Mylar or Kapton, covered (at one side or at both sides) with a coating of aluminium, silver, or gold. MLI blankets often contain spacers (e.g. course-netting material) to keep the shields properly separated. MLI reduces the heat flux rate between a hot and a cold boundary surface, thus preventing large heat leaks. Cryogenic storage systems, sensors, payloads, and full-size satellite (sub-) systems can be wrapped in insulation blankets to thermally isolate them and reduce the thermal control requirements.

Models describing the thermal performance of evacuated MLI blankets are usually based on the simple addition of the three mutually interacting modes of energy transfer, being:
- Radiation between the shields.
- Solid conduction, via the components and their interfaces.
- Gas conduction in the interstices, determined by residual gas pressure, the outgassing of the shields and spacer materials, and the way the outgassing products migrate through the blanket.

MLI blankets for spacecraft applications are usually made of perforated shields to allow a fast depressurisation during the spacecraft launch. Unfortunately, the perforations impair the insulation quality of a blanket, because:
- The perforation holes increase the effective shield emissivity, hence the radiation transfer.
- The holes allow broadside pumping: Outgas products migrate via the holes, from interstice to interstice, gradually accumulating until they eventually escape at the blanket boundary.

All reported models concern purely edge pumped blankets, consisting of non-perforated shields (MLI blankets in Dewars, vessels to store cryogenic liquids). Outgas products can escape in these blankets only at the edges of the interstices. The pumping in MLI blankets for spacecraft usually is hybrid pumping, a combination of edge and broadside. Consequently a model to account for this hybrid pumping has been developed and is presented here.

The presented results of experiments, carried out on several blanket samples using a guarded hot plate calorimeter placed in a vacuum chamber, illustrate a good agreement between theory and experiment.

This lecture is based on our article published in the proceedings of the 7th International Heat Transfer Conference, Munich, Germany, 1982. It proved to be the crucial item in a discussion on incorrect MLI modelling by Fermi Laboratory researchers. As a consequence of this discussion the editor of the journal Cryogenics (Dr. Mendelsohn) sent me a letter containing the following statement:
"Obviously the 'cryogenics community' has missed your thorough and valuable publication (maybe as it was presented at a heat transfer conference). Though it is not the policy of Cryogenics to republish articles already published elsewhere, we offer you to republish your paper in our journal".

INTRODUCTION

The models describing the thermal performance of evacuated MLI blankets are usually based on the simple addition of the three mutually interacting modes of energy transfer, being:
- Radiation between the shields.
- Solid conduction via contacting components.
- Gas conduction in the interstices, determined by residual gas pressure, outgas and the way of migration of outgas products through the blanket [1,2].

Good agreement between experimental results and results predicted by the aforementioned models has been reported [3,4], but only for blankets with non-perforated shields where the gas molecules escape in radial direction at the blanket edges (the so-called purely edge pumped blanket).

But blankets for space applications usually consist of perforated shields in order to allow for fast depressurisation during spacecraft launch. The perforation of the shields impairs the insulation quality of a blanket in two ways, being:

- First: The enhanced radiation transfer caused by an increase of the effective shield emissivity due to the perforation holes.
- Second: The enhanced gas conduction due to broadside pumping i.e. the migration of the outgas molecules through the blanket: starting at the impervious hot boundary flow of gas molecules gradually increases from interstice to interstice (by the interstitial outgas) until the flow eventually escapes to space.

One of our earlier publications on the subject [3] presented a model for this pure broadside-pumping case. It reported also a considerable discrepancy between experimental and predicted results. The discrepancy is obviously due to the fact that the model was based on pure broadside pumping while in experimental blankets, like in almost all blankets for space application, pumping is by the simultaneous of action and broadside pumping.

The general model presented here accounts for this hybrid pumping action. Predicted and experimentally determined blanket performances will be compared.

MODELLING

The model is developed for an evacuated circular multilayer insulation blanket placed between a hot and a cold boundary. This is schematically depicted in figure 1. The boundary temperatures are T_H and T_C. The boundary emissivities are ε_H and ε_C.

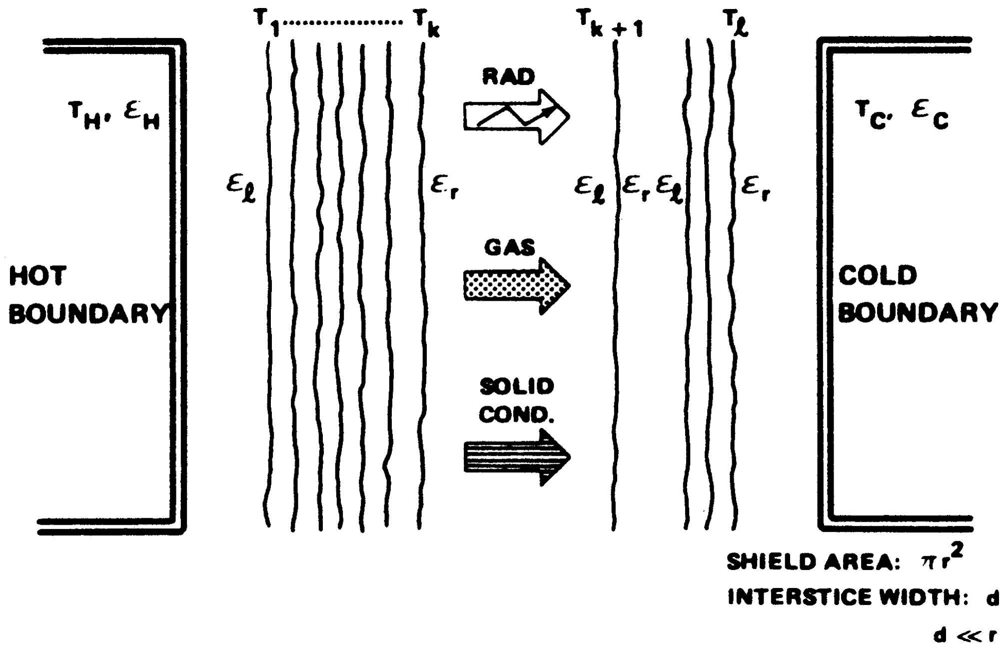

Figure 1. MLI blanket (schematic).

The blanket consists of ℓ more or less parallel identical shields with left side emissivity ε_ℓ and right side emissivity ε_r. The shields are perforated: perforation grade T, the open shield area divided by the total shield area (πr^2). The interstice gap width is d (d << r). The shield thickness is so small that the shield temperature can be taken to be uniform (for shield k: T_k).

In the considerations the gas is assumed to flow from the hot towards the cold boundary, as it occurs in the case of insulation of a hot black box from cold space environment. This assumption is not a basic one. The model also applies for cryogenic vessel insulation (the cryogen at the cold side, the low-pressure environment at the hot boundary) by a simple interchange of the suffixes H and C in the governing equations.

Assumptions

It will be assumed that the interstitial medium is optically thin. As discussed in the literature [1,2], this implies that the contributions of the three modes of energy transfer (radiation, gas conduction and solid conduction) can be simply added.

It also will be assumed that the interstitial gap width is small compared with the mean free path of gas molecules. This assumption and the assumption that the blanket shields are outgassing according to Arrhenius Law are basic for the form of the gas conduction term in the heat transfer equations describing the thermal performances of the blanket considered [4].

General equations

The energy transfer in the optically thin defined blanket can be described [3,4] by a set of ℓ+l equations:

$$q = A_{H,1}(T_H^4 - T_1^4) + B_{H,1}\sqrt{T_H T_1}(\sqrt{T_H} - \sqrt{T_1}) + C_{H,1}(T_H - T_1).$$

$$q = A_{k,k+1}(T_k^4 - T_{k+1}^4) + B_{k,k+1}\sqrt{T_k T_{k+1}}(\sqrt{T_k} - \sqrt{T_{k+1}}) + C_{k,k+1}(T_k - T_{k+1}) \qquad (1)$$

$$q = A_{\ell,C}(T_\ell^4 - T_C^4) + B_{\ell,C}\sqrt{T_\ell T_C}(\sqrt{T_\ell} - \sqrt{T_C}) + C_{\ell,C}(T_\ell - T_C),$$

q is the heat flux through the blanket (W.m^{-2}) and the first right hand side terms represent the radiation transfer, the second terms represent the heat transfer by gas conduction and the last terms represent the heat transfer by solid conduction (contact conductance). The three models of transfer are discussed in the following sections.

Solid conduction

As the solid conduction in the shield is assumed to be very large (uniform shield temperature), the solid conduction parameters $C_{H,1}$ … $C_{k,k+1}$ … $C_{\ell,C}$ are contact conductances. For the blanket one can write

$$C_{1,2} = C_{2,3} = \dots C_{k,k+1} = \dots C_{\ell-1,\ell} = C,$$

$$C_{H,1} = C_H \ , \qquad (2)$$

$$C_{\ell,C} = C_C \ .$$

Radiation transfer

The expressions for the radiation parameters can be derived to be

$$A_{H,1} = \sigma / [\varepsilon_H^{-1} - 1 + E^{-1}\varepsilon_r / (\varepsilon_\ell + \varepsilon_r)] \ ,$$

$$A_{K,K+1} = \sigma / [E^{-1} - 1], [\qquad (3)$$

$$A_{K,K+1} = \sigma / [E^{-1} - 1],$$

σ is the Stefan-Boltzmann constant (Wm^{-2}K^{-4}) and

$$E = \tau + (1 - r)\varepsilon_\ell \varepsilon_r / (\varepsilon_\ell + \varepsilon_r). \qquad (4)$$

These equations are generalisations of earlier presented equations [4,5], that are valid only for equal left and right side shield emissivities:

$$\varepsilon_\ell = \varepsilon_r$$

Gas conduction

The gas conduction parameters depend on the residual interstitial gas, the interstitial gas pressure, the outgas properties of the blanket components and the way of gas migration through the blanket. The general form for the *B*-terms is [3,4]

$$\mathrm{B}_{k,k+1} = \left[(4+f)^2 R / 2\pi M\right]^{1/2} \left[P_0 / T_0 + (\upsilon_1 R / dM) F_K\right], \tag{5}$$

Where

- f denotes the number of degrees of freedom of the gas particles,
- R is the universal gas constant ($\mathrm{J.kmol^{-1}\,K^{-1}}$)
- M is the molecular weight of the gas molecules ($\mathrm{kg.kmol^{-1}}$)
- P_0 is the environmental (or residual) gas pressure ($\mathrm{N.m^{-2}}$)
- T_0 is the ambient temperature corresponding with P_0 (K)
- d is the average interstitial gap width (m)
- υ_1 is the outgas constant υ_0 integrated over one second, representing the number of molecules per square meter present in the interstice ($\mathrm{kg.m^{-2}}$).
- F_k defined in the next section, represents the temperature dependent outgas in the interstices and the way the outgas products migrate through the blanket.

Outgas

Outgas in MLI blankets is a combination of de-sorption of by the shield surfaces absorbed molecules (impurities) and the evaporation of blanket material (degradation). The outgassing phenomenon is schematically elucidated by figure 2.

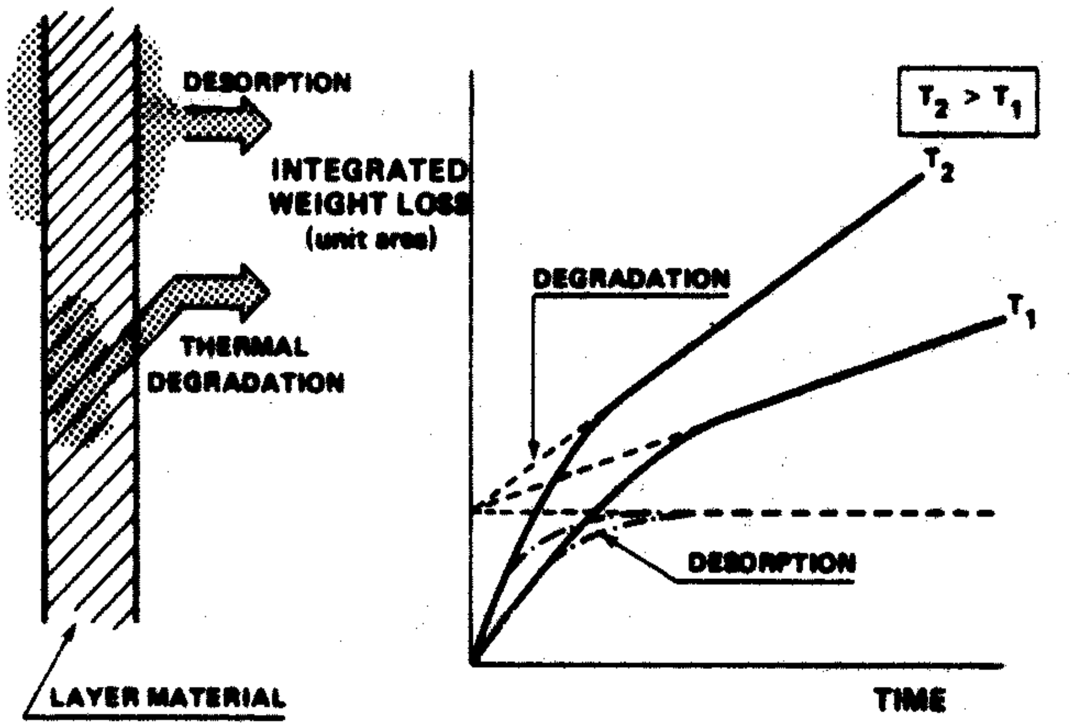

Figure 2. Outgas of a blanket shield.

The desorption process is relatively short lasting (until all impurities have been de-sorbed from the surfaces), hence can be neglected in long-term blanket performance.

Degradation of the blanket materials can be described by the law of Arrhenius.

$$\upsilon = \upsilon_0 \exp(-\alpha / T), \tag{6}$$

as it is confirmed by experimental results reported [6,7]. In equation (6) υ represents the outgas rate (kg $m^{-2}s^{-1}$) and T is the surface temperature (K). The constants α (K) and υ_0 (kg $m^{-2}s^{-1}$) characterise the outgas rate of the blanket material involved.

More detailed information with respect to outgas phenomena can be found in literature [5 to 10]. Values for α and υ_0 for different blanket materials are indicated in figure 3. They have been derived from experimental data presented [6,7]. The line indicates the calculated boundary between regions with and without noticeable influence of the outgas phenomenon on the thermal performance of 100 layer blankets.

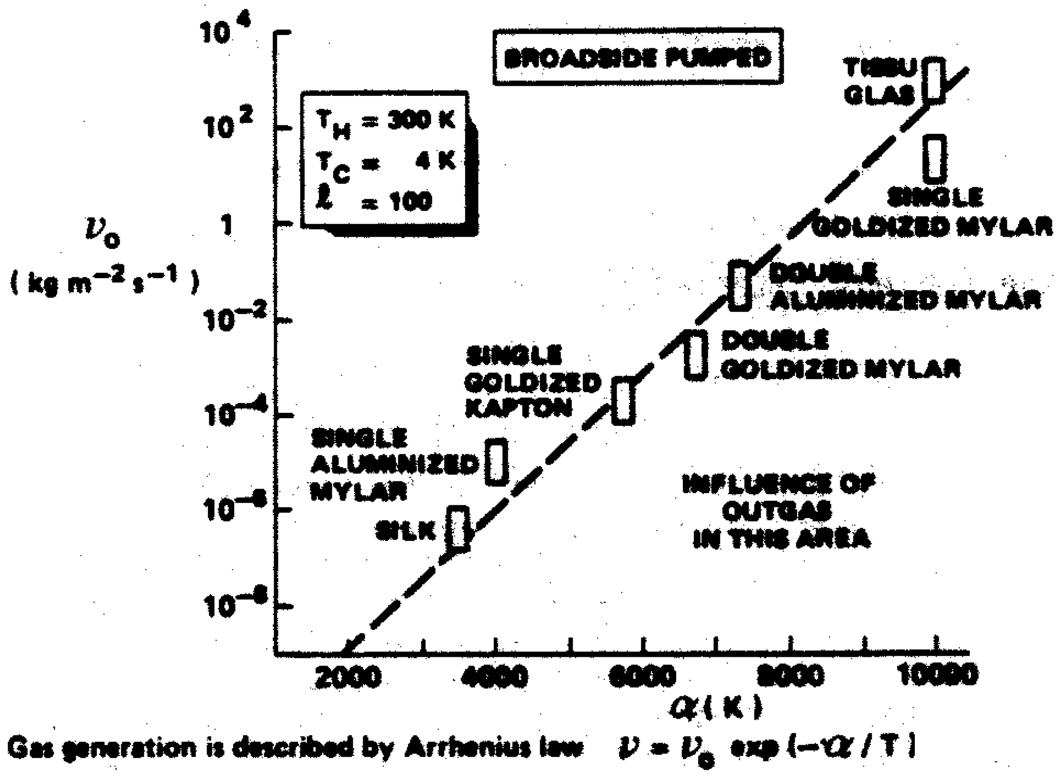

Figure 3. Parameters for blanket materials.

The factor F_k is determined by outgas properties and the way outgas products migrate through the blanket to the environment. The approach followed is based on the philosophy that under equilibrium conditions the outgas rate equals the pumping rate.

For edge pumped blankets (made of non-perforated shields) outgas generated in the k-th interstice, hence determined by the two shield temperatures T_k and T_{k+1}, will escape at the interstice edges only. For these blankets one can write

$$F_k = exp(-\alpha / T_k + exp(-\alpha / T_{k+1}). \qquad (7)$$

For purely broadside pumped blankets (having perforated shields and sealed edges) outgas products move via the perforation holes towards the environment (cold boundary). This means that not only outgas in the k-th interstice contributes to the gas conduction in this interstice, but also all outgas products generated in the interstices between k and the impervious boundary (at k = 0).

In other words F_k represents an accumulated outgas, described for this broadside pumped case by:

$$F_k = \exp(-\alpha / T_H) + (1-\tau)\left[\sum_{i=1}^{k} Z \exp(-\alpha / T_k) + \exp(-\alpha / T_{K+1})\right] \qquad (8)$$

The factor 1-τ results from the reduced outgas area (holes do not outgas).

For actual blankets in space the migration of outgas products will occur both in the edge and broad side directions simultaneously. For such blankets one can derive:

$$F_K = \gamma^{k-1}\exp(-\alpha/T_H) + (1-\tau)(\gamma+1)\sum_{i-1}^{k} \gamma^{k-1}\exp(-\alpha/T_i) + \\ + (1-\tau)\exp(-\alpha/T_{k+1}) \tag{9}$$

Where γ represents the ratio of the perforated area to the sum of this area and the edge area, hence:

$$\gamma = \pi r^2\tau/(\pi r^2\tau + 2\pi r d) = (1 + 2d/\tau r)^{-1}\ . \tag{10}$$

Finally it can be remarked that in the case of cryogenic vessel insulation, with the impervious wall at the cryogenic side (k=0) and the pumping environment at the hot side ($T_H = T_{\ell+1}$), all foregoing equations can be applied of one interchanges the suffixes H and C.

EXPERIMENTAL ISSUES

A guarded hot plate calorimeter was built to carry out experiments to verify the validity of the developed model. Figure 4 shows a schematic and a photograph of this test rig, which is operated in vacuum. It consists of two vessels, 0.3 m in diameter, facing each other. The opposing circular surfaces are covered with a black coating ($\varepsilon_H = \varepsilon_C = 0.925$). The distance between the two vessels is adjustable between 0 and 2.5cm.

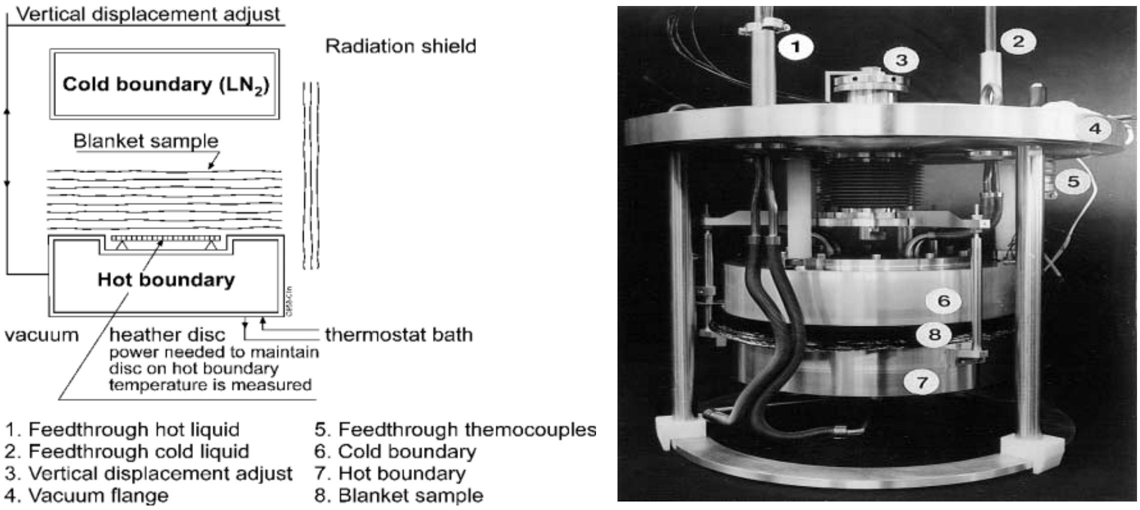

Figure 4. MLI test rig.

The test blanket is located in the spacing between the vessels. The upper vessel, filled with liquid nitrogen is the cold boundary; the lower vessel, the hot boundary, is connected to a thermostat bath. The central part of the lower vessel consists of a 0.15m diameter heater disc, mounted thermally insulated from the vessel.

The temperature difference between disc and lower vessel is measured by thermocouples and is kept below 0.05K by controlling the disc heater power. In thermal equilibrium the dissipated power cannot be radiated or conducted to the surrounding lower vessel (since the temperature difference approaches zero), hence it will be transferred through the test blanket. This power is measured.

The test blanket used consists of 25 layers crinkled single aluminised mylar (SAM). The aluminised sides of the shields are directed to the hot boundary. Five layers of the blanket are equipped with thermocouples to measure the temperature distribution inside the blanket. T_H and T_C are measured also. Measurements were carried out at the ultimate pressure of the vacuum system for different distances between hot and cold boundary. The heat flux as a function of this distance is shown in figure 5.

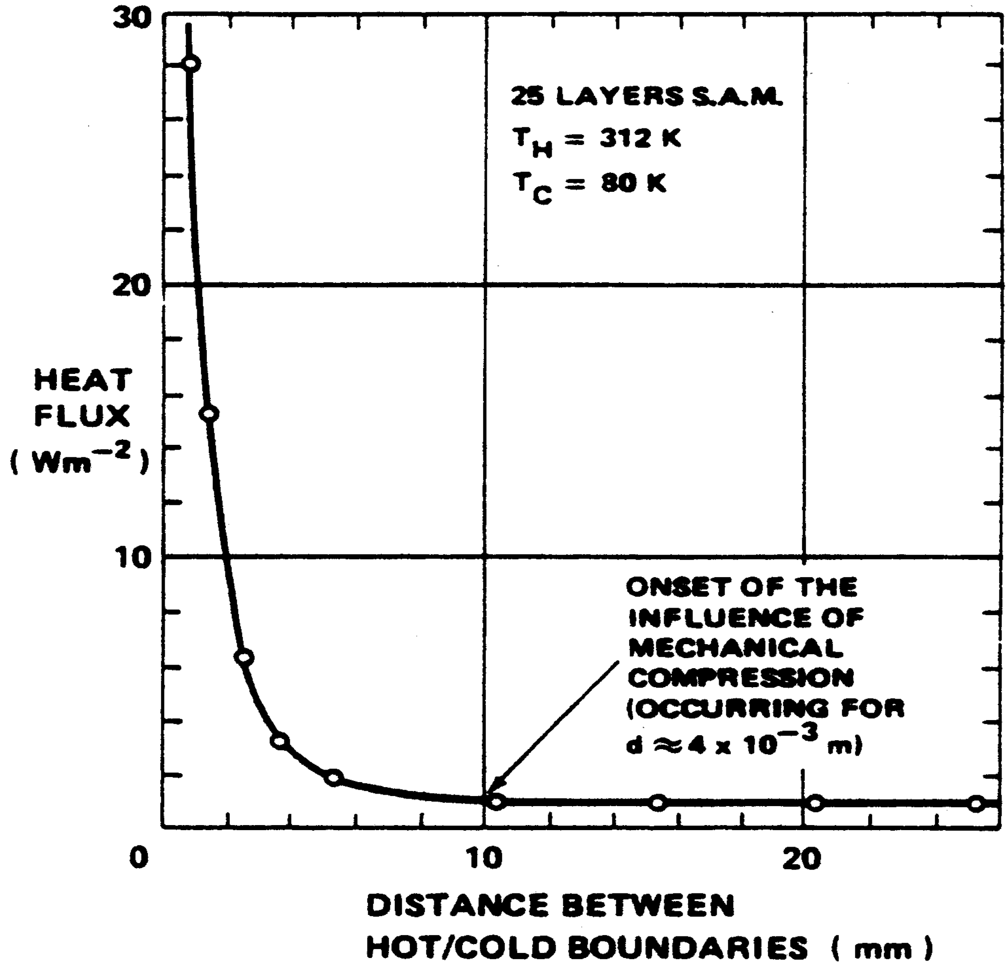

Figure 5. The experimental determination of the onset of the effect of mechanical compression.

From this figure it can be concluded that the sharp rise in the heat flux is due to mechanical compression of the blanket causing increase of the contribution. The smallest distance not affected by compression was taken to be the most suitable distance for this particular blanket.
Further measurements were carried out at a number of environmental pressures for a blanket that was edge pumped only (no perforation of the shields). The adjusted vacuum chamber pressure was maintained at least during four hours prior to each actual measurement. The test blanket was perforated, by piercing each layer (with a knife) at about 700 spots. The resulting perforation grade is estimated to lie within the range of 0.002 to 0.005 (depending how far the slits opened in vacuum).

COMPARISON BETWEEN THEORY AND EXPERIMENT AND CONCLUDING

Figure 6 presents a comparison of the thermal performances of the test blanket: Experimentally determined performances are indicated by solid dots, performances calculated according out model for different values of τ (hence γ) are represented by the solid lines.

From this figure it can be concluded that the model developed accurately describes the thermal blanket performance, especially at lower pressures. The deviation between experiment and theory at higher pressures is a direct consequence of the fact that the model applies only if the molecular mean free path is much larger than the interstitial distance. This requirement is not fulfilled for higher pressure values.

In summary:
- Calculations have been performed for various blanket materials (υ_0, α-combinations) in order to identify possible application areas for the model i.e. those cases for which the outgassing phenomenon considerably influences blanket performances. As an example, the results are shown (Fig. 3) for purely broadside pumped blankets consisting of 100 layers (large outgassing area)

between a hot boundary of 300K and cold space (4K). The line separating the areas of negligibility and non-negligibility of the outgas shifts downwards at higher hot boundary temperatures.

- The experimental data agree with modelling outcomes: The model is mature for MLI blanket design.

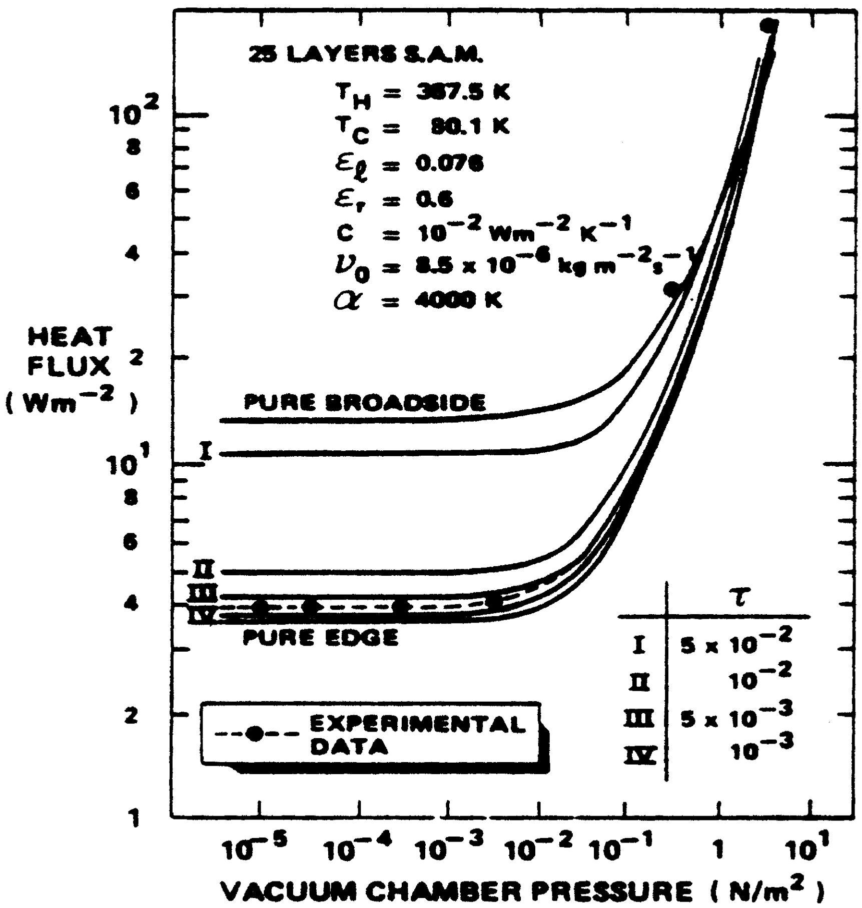

Figure 6. Comparison between predicted and measured thermal performances.

NOMENCLATURE

A	radiation parameter	$Wm^{-2} K^{-4}$
B	gas conduction parameter	$Wm^{-2} K^{-3/2}$
C	solid conduction parameter	$Wm^{-2} K^{-1}$
E	quantity defined by parameter	-
F	outgas effect factor	-
M	molecular weight	$kg\ kmol^{-1}$
R	universal gas constant	$J\ kmol^{-1} K^{-1}$
T	temperature	K
d	interstitial width	m
f	degrees of freedom (molecular rotation)	-
ℓ	number of shields	Nm^{-2}
P_0	residual gas pressure	-
q	heat flux	Wm^{-2}
α	outgas constant	K
γ	shape factor	-
$\varepsilon_\ell, \varepsilon_r$	thermal emissivity (left and right side of shield	-
υ_0	outgas rate	$kg\ m^{-2} s^{-1}$
υ_1	outgas rate integrated over 1 second	$kg\ m^{-2}$
σ	Stefan-Boltzmann constant	$Wm^{-2} K^{-4}$
τ	perforation grade	-

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